LIGO Detector Electromagnetic Compatibility Upgrade

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Review outline

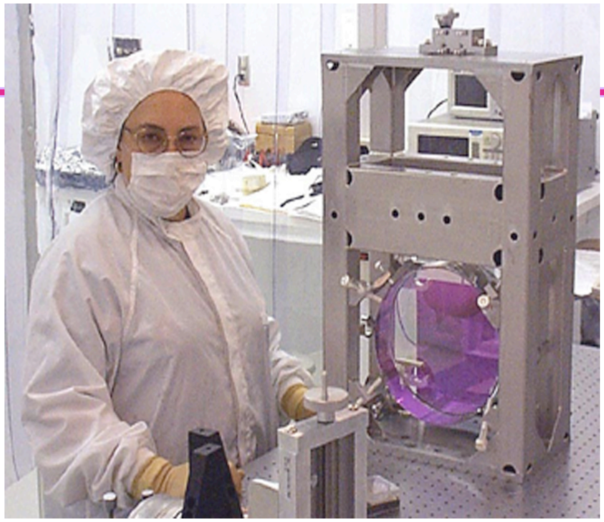
- Introduction & charge (Rich)
- As-built problems & issues (Mike)
- Proposed strategy (Mike)
  - Lessons from other “low noise” endeavors
  - LIGO-specific constraints & compatible responses
- Conceptual design (Jay)
- Installation & test phasing (Jay)
- Cost estimate (Mike)

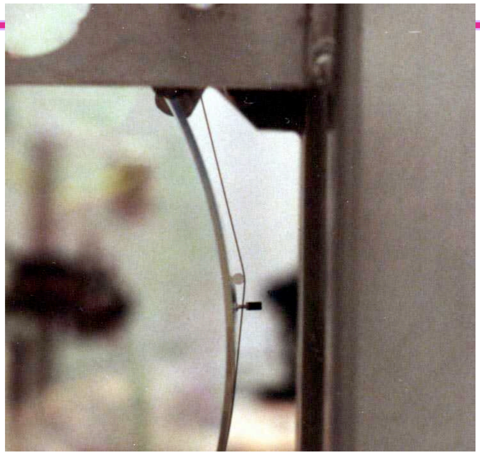
We will not present a point-by-point defense of requirements in this review

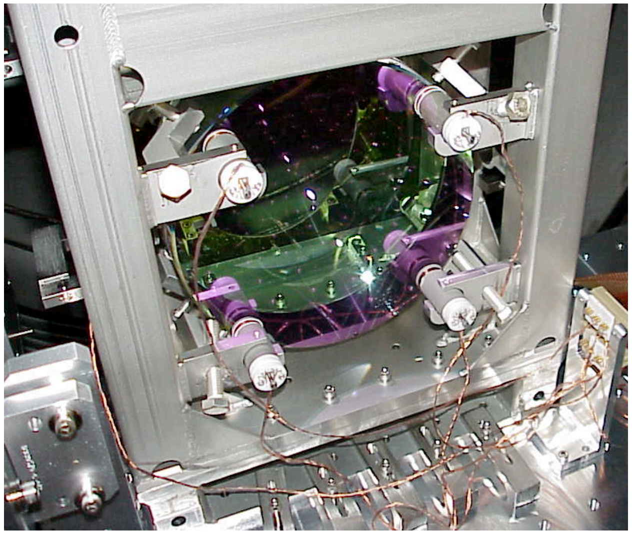
LIGO Electronics Overview

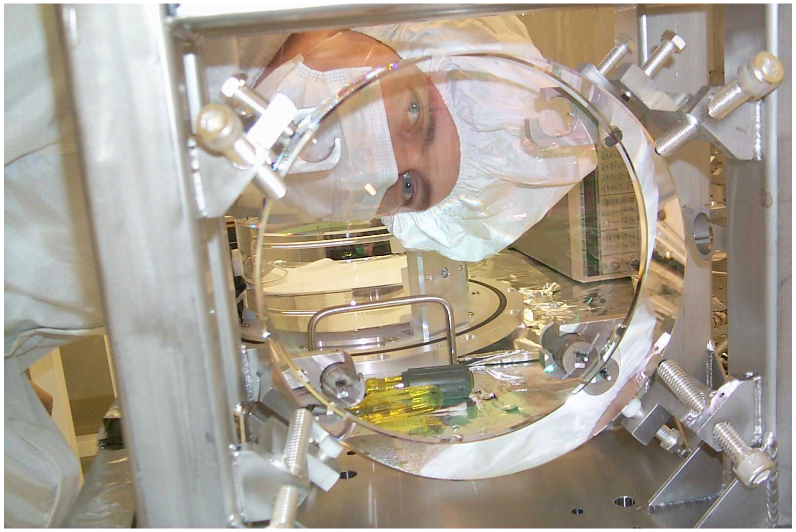
- Interferometers are *sensitive*, but not very *linear*, at least not w/out help
  - Mirrors angles must be steady within about 10^{-8} radian
  - Mirror separations must be integral no. of laser half-wavelengths, within about 10^{-12} m
  - Seismic motions at low frequencies are several orders of magnitude larger
  - *FEEDBACK CONTROLS* are needed to hold operating points & extract "signal-band" mirror disturbances for readout & analysis
- Array of photodiode sensors used to measure lengths & angles
  - RF sidebands "tag" light beams circulating in different parts of the interferometer
  - Demodulated photocurrents give length & angle errors for combinations of mirrors
- Signal processing is (mostly) digital
  - Many degrees of freedom
  - Challenging filter design problems (RMS @ 1 Hz > 10^9 * noise @ 40 Hz)
  - Fast parametrics & state changes required during startup ("lock acquisition")
  - VME-based, VxWorks OS on Pentiums; 'reflective memory' data transmission; GPS timing
- Currents through magnetic coils force tiny permanent magnets on IFO mirrors to maintain operating points
- Also need
  - Supervisory controls& monitoring (VME + Sun operator consoles, EPICS software)
  - Global diagnostics (VME + Sun)
  - Data acquisition system (VME + Sun)

Core Optics Suspension and Control

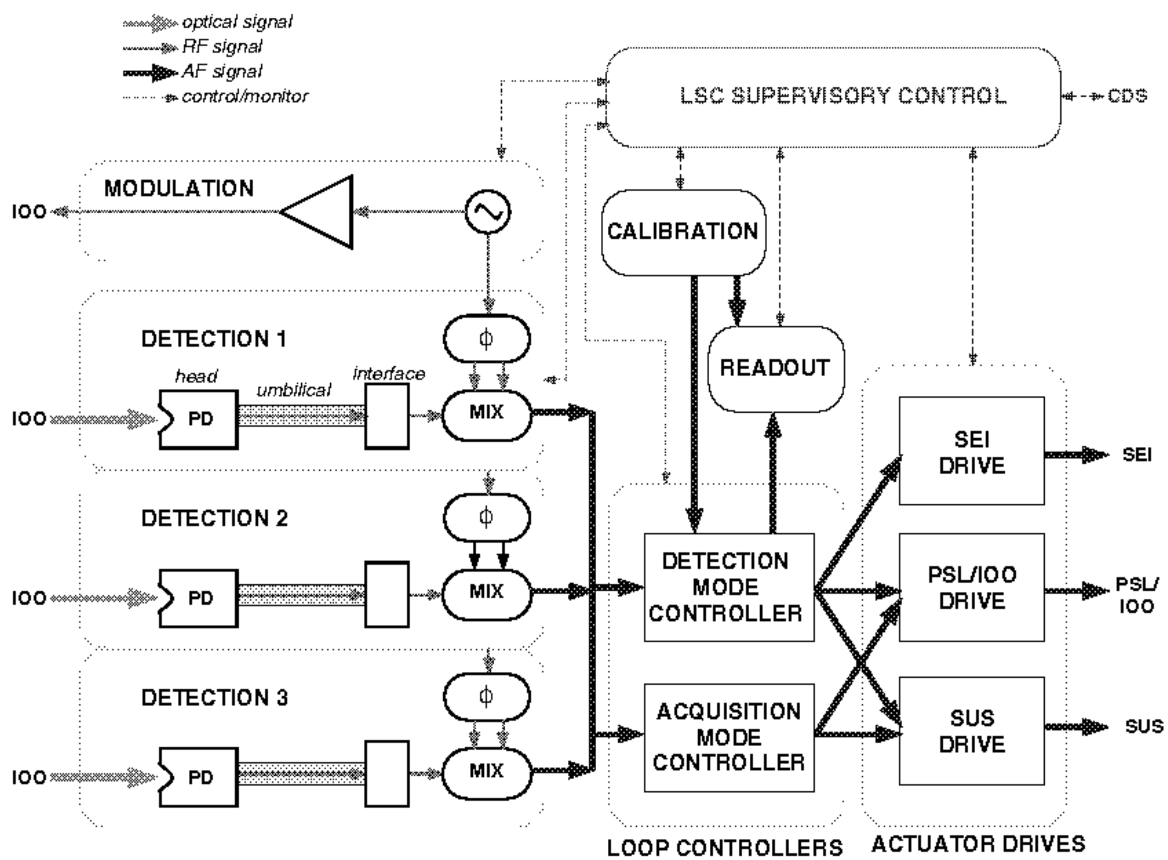




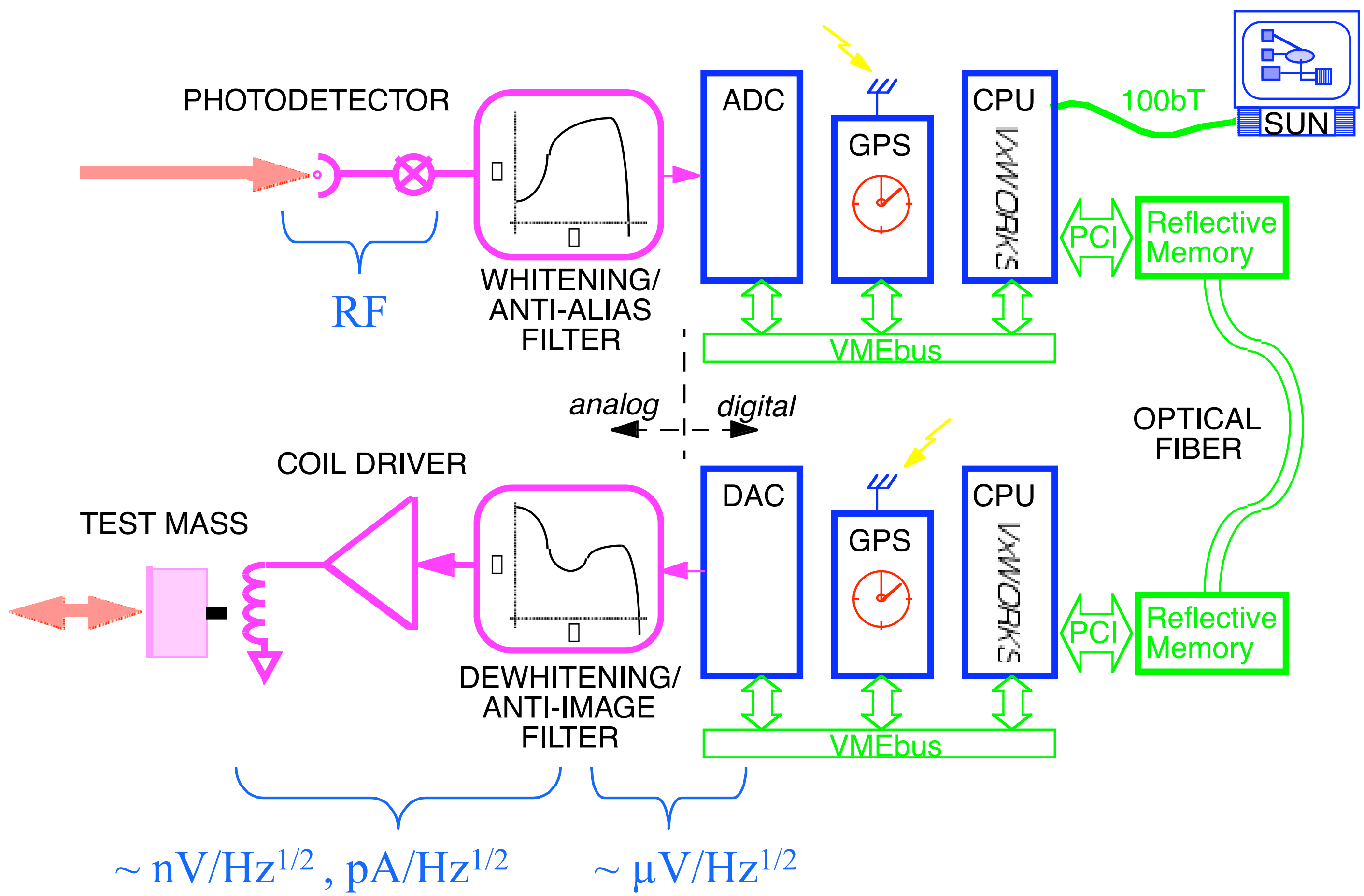




Functional Block Diagram (sensing & control)



LIGO Control Signal Processing Architecture (simplified)



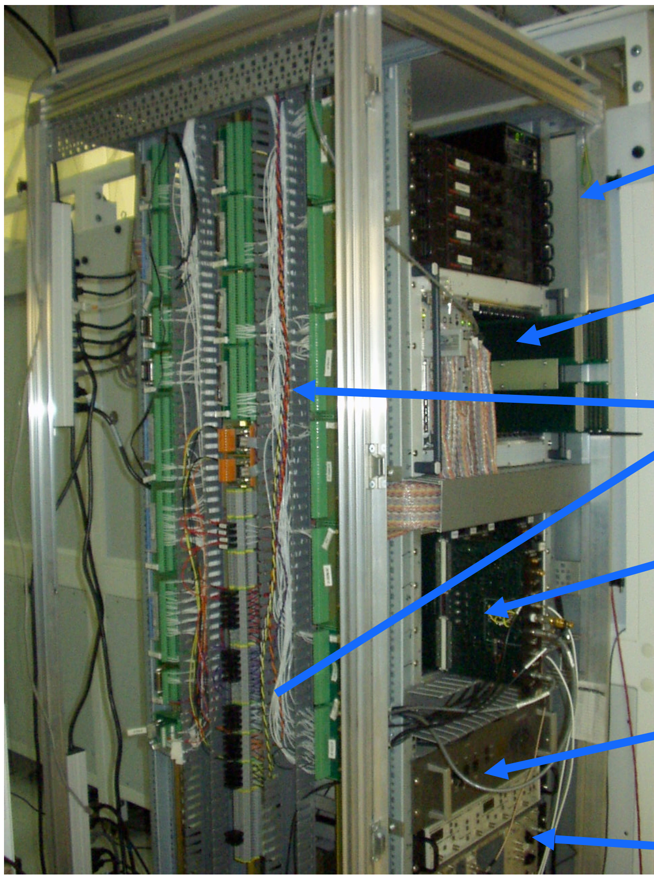
What/Where/How Many?

- Each interferometer has (partial list):
  - ~18 EIA electronics racks
  - ~14 VME crates
  - ~12 analog/RF Eurocard crates + ~ 10 19” rackmount chassis
  - ~22 photodetector heads (RF, WFS, optlev, ETM, etc.)
  - ~24 microphones, accelerometers, seismometers
  - ~60 in-vacuum magnetic force actuators,
- Located in:
  - Rack clusters in corner station and each end station
  - Sensor tables & platforms arrayed around vacuum envelope
  - Inside the vacuum envelope
- Connected via
  - Optical fiber (data, including all end station signals)
  - Coax (RF, some analog signals within station)
  - Twisted pairs (inter-rack analog signals within station)
  - Ribbon cables (within & between racks)

LIGO Electronics SNR Requirements

- Analog front and back end BOTH at ~ thermal noise limit
  - nV/$Hz^{1/2}$ and pA/$Hz^{1/2}$ characteristic noise levels for photodetector signals AND mirror drive signals
  - "whitened" to fit ADC and DAC ranges (~ μV/ $Hz^{1/2}$ at converters)
  - Most critical in audio signal band 40 Hz - 8 kHz
  - Also applies to ± sidebands near RF carriers (24.5, 29.5 MHz)
- Susceptible to nonlinearity
  - Huge out-of-band signals at low frequencies (seismic noise)
  - HF noise rises sharply again as stabilizer control gains poop out
  - Intermodulation & rectification hard to control at nV levels
- Low tolerance for line hum
  - Complicates data analysis
  - Some searches (e.g., periodic) affected more than others (e.g., stochastic);

Original architecture: RF & analog laser controls w/ EPICS VME crate in MIT lab



switching power supplies

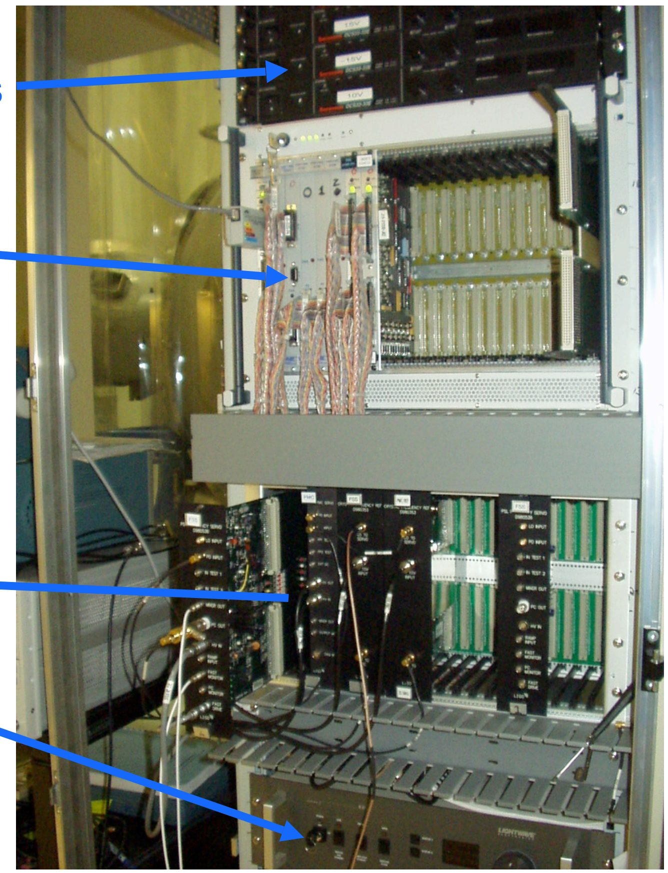
VME crate

cross-connect blocks

analog/RF Euro crate

laser controller

more supplies



RF Photodiode Module

power, monitor & state control

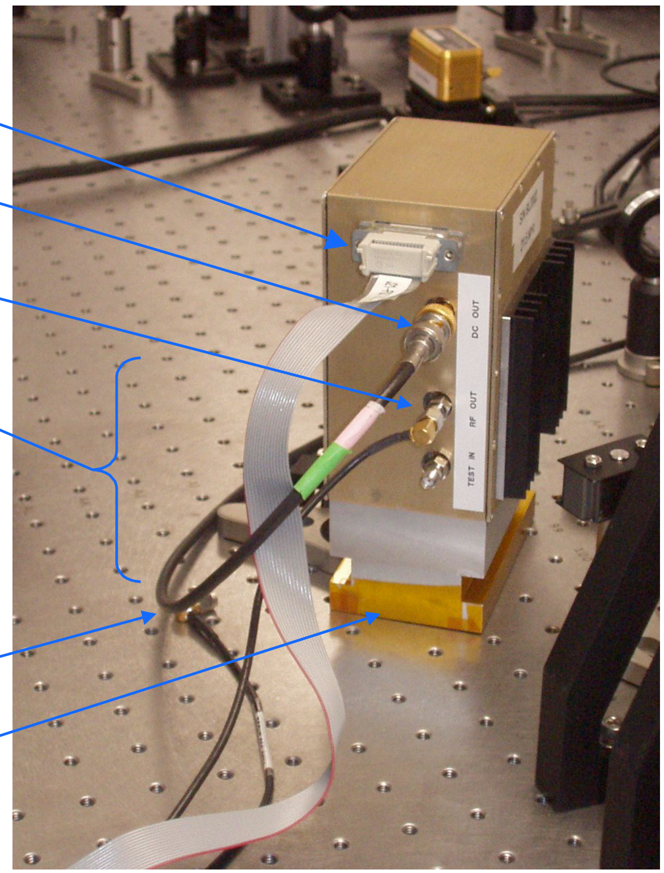
DC output

RF output

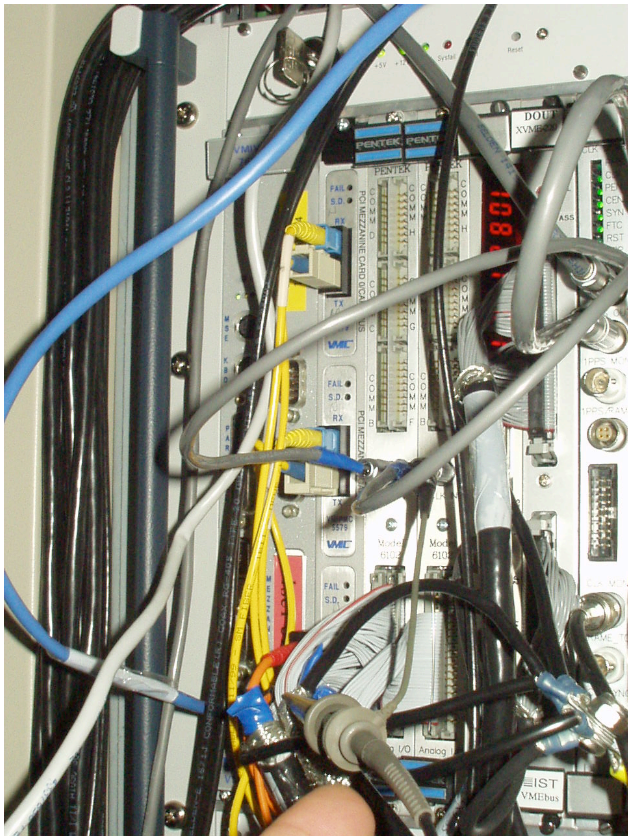
cables follow different paths
back to different
crates/terminals

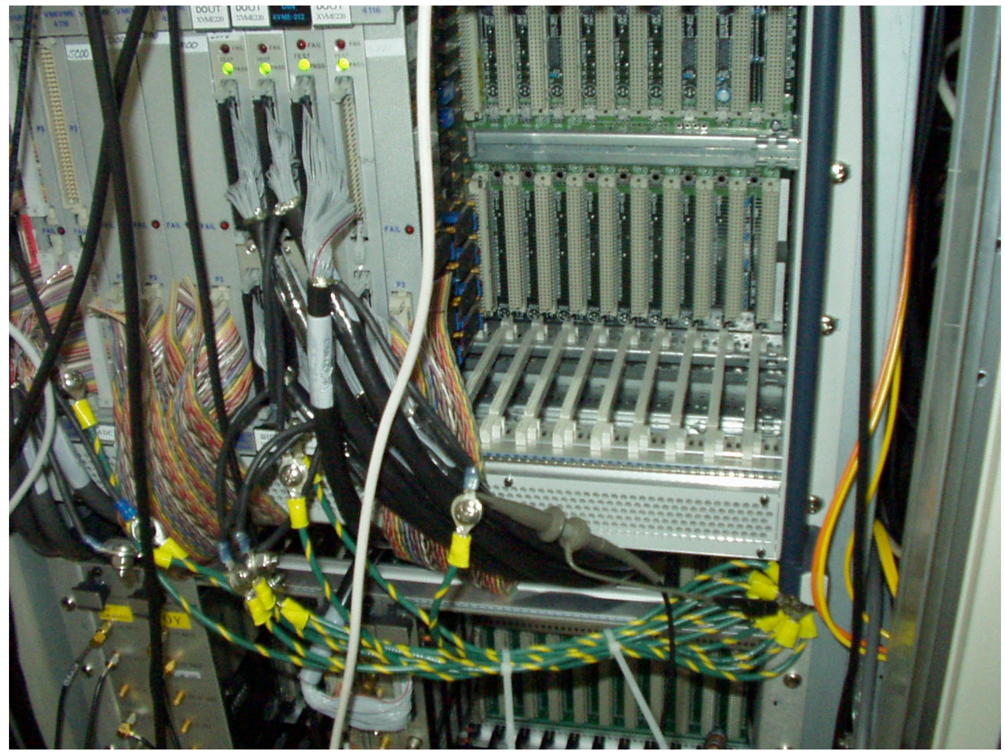
Doh!

Kapton tape

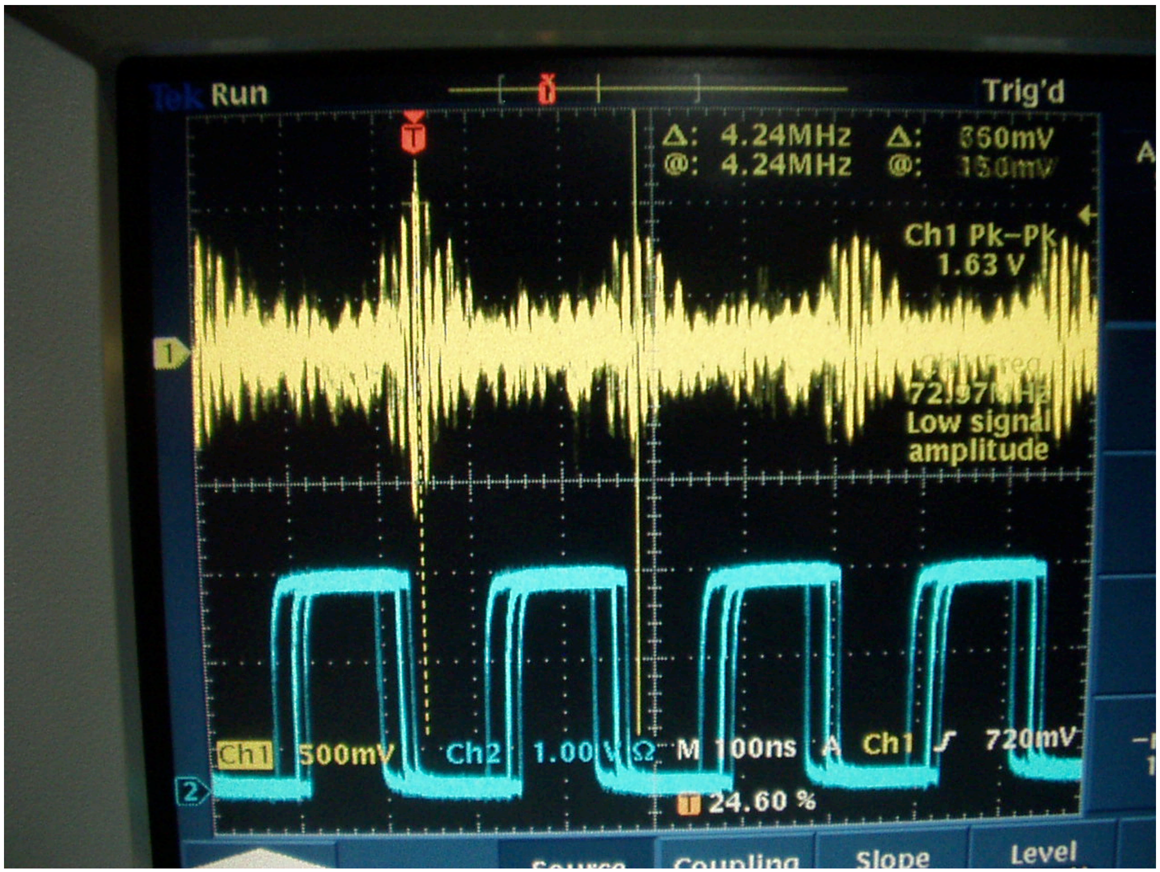


'Evolution:' LSC & EPICS VME crates @ LLO

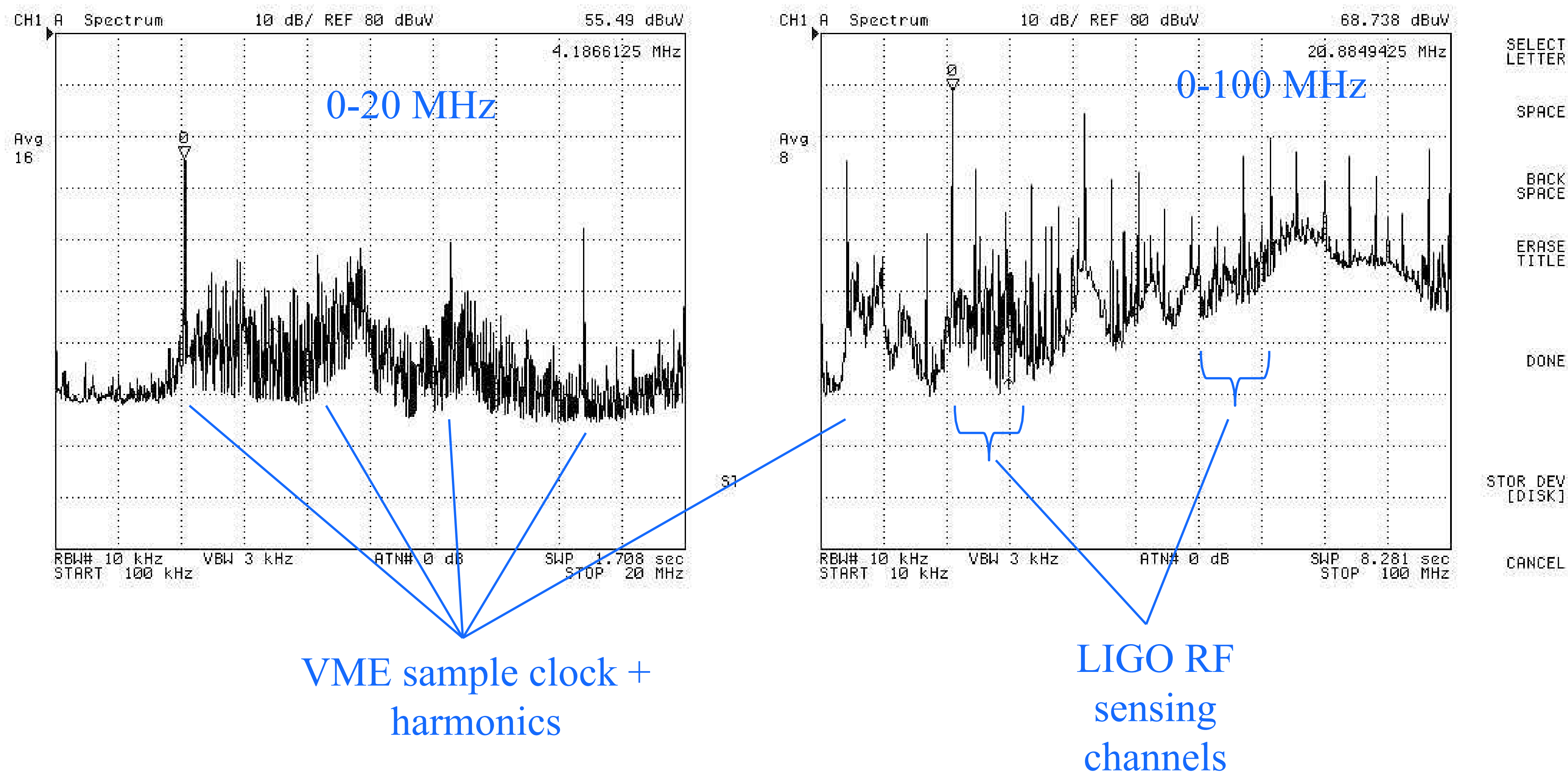




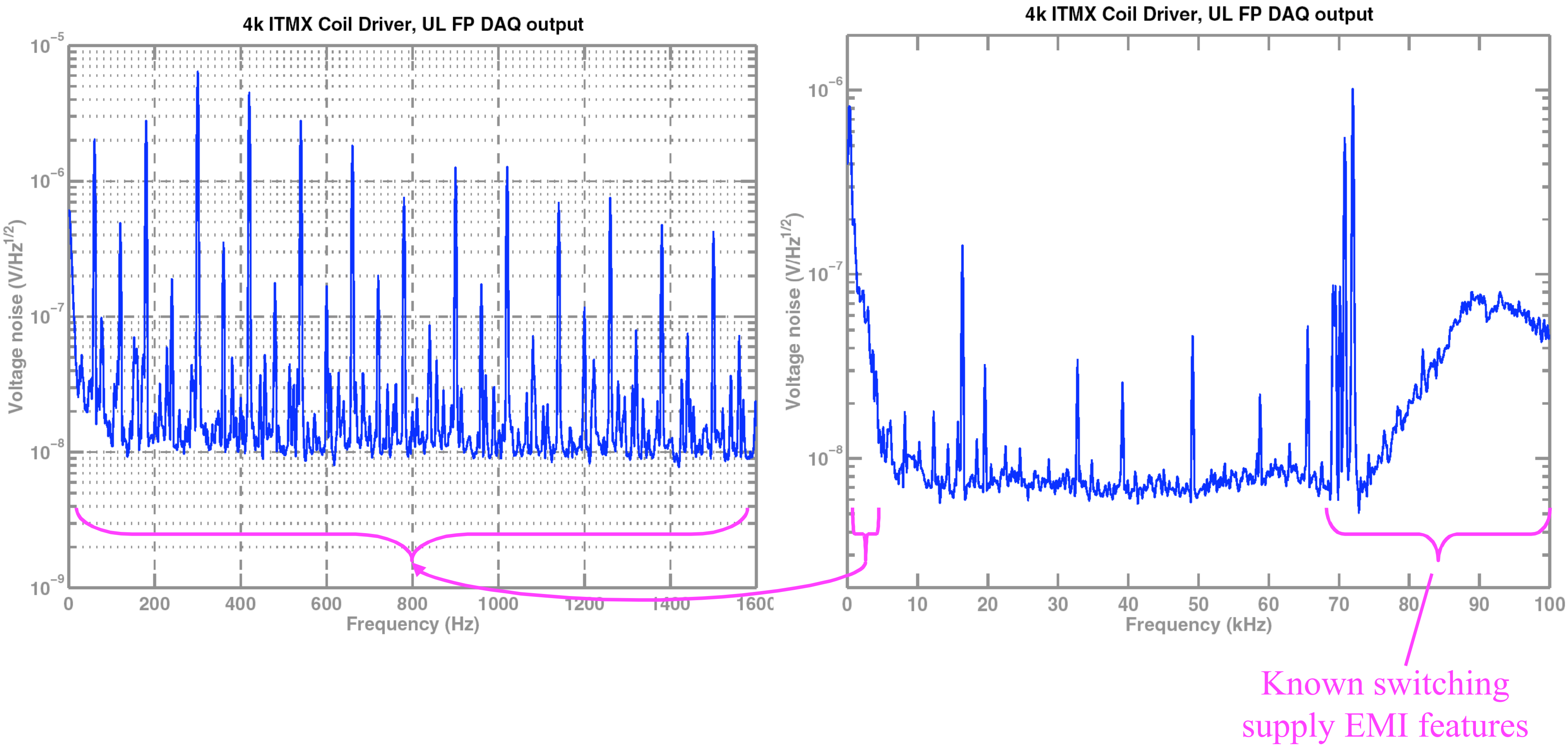
ADC input signal hash (top), main clock (bottom)



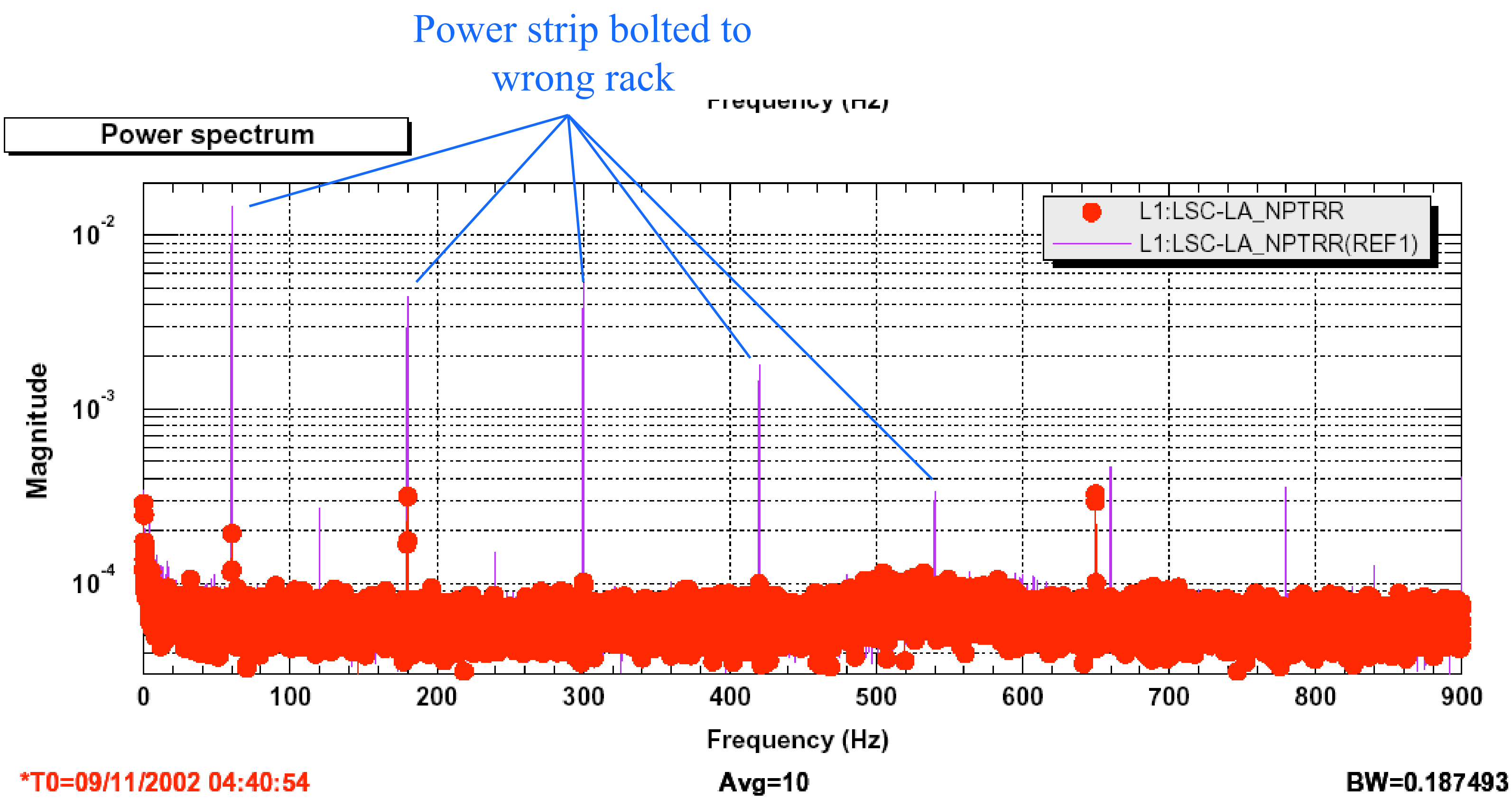
18 cm dipole 1m from VME crate



Spurious lines due to fans & switching supply radiation (H1 ITMx)



Ground loop example: ETMx transmission monitor



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Interaction Mechanisms & Frequency Bands

- Linear
  - Baseband
    - ground loops
    - electrostatic & magnetic coupling
    - supply coupling
  - RF (modulation frequencies ± 10 kHz)
    - direct radiation & conduction
- Nonlinear
  - Rectification
    - audio circuit slew rates < V/μs, digital clock RFI slopes > V/ns
  - Intermodulation
    - strong RF lines spaced by audio frequency “mix down” to audio noise
  - Sample aliasing
    - All frequencies present at ADC sampler are aliased into 0-8 kHz band

Summary of As-Built Issues

- Self-inflicted EMI sources
  - DC switching power supply radiation & conduction
  - 60 Hz ground loops & magnetic coupling
  - VME crate digital hash radiation & conduction
- Analog/RF circuit vulnerabilities
  - poor (or no) circuit shielding (rack, crate, chassis & board level)
  - poor (or no) cable shielding (open cross-connects, ribbon cables)
  - multiple ground paths & loops

Possible Mitigation Approaches

- Start over from scratch (prohibitive) ✗
- Fix specific things as they're discovered (as doing now) ✗
  - Nonlocal: global interactions, many modules typically participating
  - Nonstationary: today's fix=tomorrow's ground loop; don't move that wire!
  - Nonlinear: can't determine "margin" below current noise backgrounds
  - Amplifies "search tree" for troubleshooting, greatly impedes commissioning
  - Depletes confidence in reality of rare or weak signals!
- Adapt existing hardware to new shielding, cabling protocols ✓
  - Replace COTS hardware (crates, racks, power supplies etc.) with "EMC-rated" functional equivalents
  - Introduce cable filtering and shielding without changing functions
  - Repackage existing boards with improved shielding
  - Change grounding and wiring to eliminate ground loops & antennas
- USE LESSONS FROM LITERATURE & OTHERS

Lessons: Power Supplies

- Lesson 1: switching power supplies suck
  - temptation: $/watt, m^3/watt, kg/watt all about 2-5x lower than linears
  - these efficiencies achieved through HF modulations (smaller transformers & capacitors), sharp switching transitions (minimal device dissipation)
  - rich RF spectra radiated & conducted, with significant internal correlations (e.g. line harmonic envelopes, etc.)
- Recommendation: sell them, buy linears
  - Already done on endstations of the L1 machine; preliminary indications of significant improvement.

More Lessons: Digital Hash

- Lesson 2: Everything digital screams
  - Sub-ns clock transitions give Fourier components > GHz
  - Bus and CPU make broadband modulation with internal structure (often sync'd with sample clocks!)
  - Induced voltages on analog lines ~ V (rectification/IMD inevitable)
- Recommendations: (with help from NRAO)
  - Use shielded digital crates
  - Segregate digital stuff in dedicated, shielded racks
  - Pass all I/O conductors through EMI filters on boundary penetrations
  - *Problem:* ADC & DAC are both analog *and* digital (technical workaround; see Jay's talk)

EMI filters

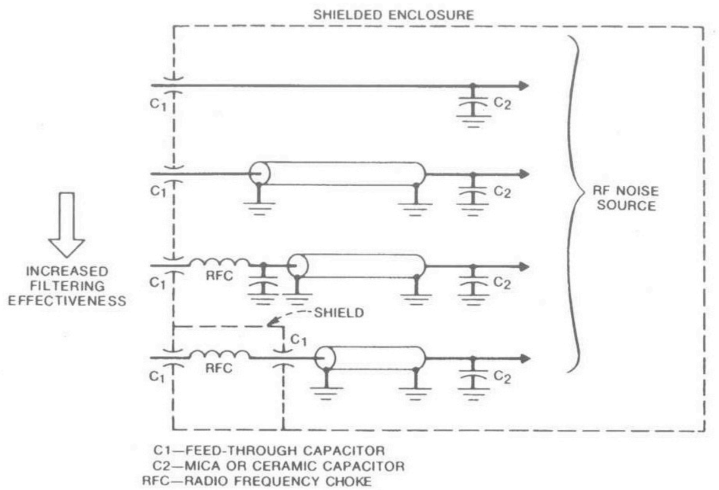

Figure 4-18. *Various high-frequency lead-filtering methods. Effectiveness increases from top toward bottom.*

- shunt RF current to shield, increase RF series impedance
- can also force common-mode rejection
- now used in critical applications on one pin at a time

- most configurations & frequency ranges commercially available on multipin connectors
- compatible with existing equipment

More lessons: Ground Loops

- Lesson 3: Break ground loops
  - o Rack-rack, remote sensor, green wire, etc. make loops, intersect flux; large 60 Hz currents (.25 A measured) run in cable shields
  - o Power, signal & control cables o remote heads run in separate cable trays, enclose flux & induce currents in sensor device
- Recommendations
  - o Bundle cabling (with internal shielding) and float remote devices
  - o Float analog circuits from racks
  - o Route mains power through isolation transformers
  - o Implement "single-point" or "star" grounding for analog units
  - o Use opto-, flux-isolated or differential drives for inter-rack signals

respect safety codes!

- *Not so fast: what about RF grounding?*

Grounding: conflict between RF/digital and LF strategies

- RF+ digital systems (e.g., radio dish): ground everything *locally* and *redundantly*
  - inductance of cable shield or ground strap ~ .2 μH/ft --> 31 Ω/ft @ 25 MHz, 120 Ω/ft @ 100 MHz
  - stray capacitance to nearby metal ~ 10 pF --> 600 Ω @ 25 MHz
  - EVERYTHING'S CONNECTED CAPACITIVELY, explicit paths ineffective
  - multiple linkages approach giant ground plane and limit radiative fields
- Low-noise audio systems (e.g., recording studio): *float everything*, direct all ground returns a single "star" point
  - n X 60 Hz currents produce varying reference potentials depending on relative impedances
  - loops couple flux to generate these currents
  - crosstalk between circuits arises from shared ground impedance
  - force all induced currents to be 'common' to both signal and reference (signal only referenced to local return)

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Ground Dilemma

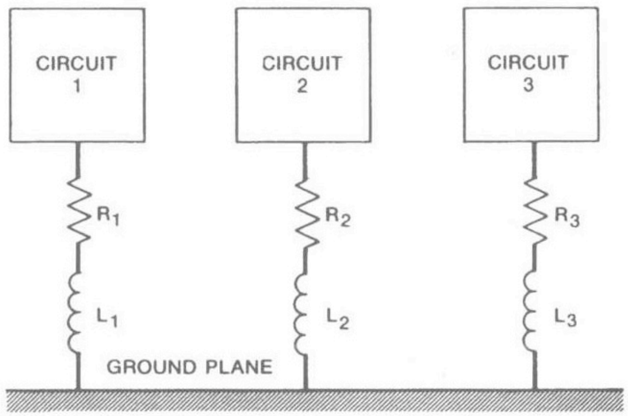


Figure 3-8. *Multipoint ground system is a good choice at frequencies above 10 MHz. Impedances R_1–R_3 and L_1–L_3 should be minimized.*

from Ott (1988)

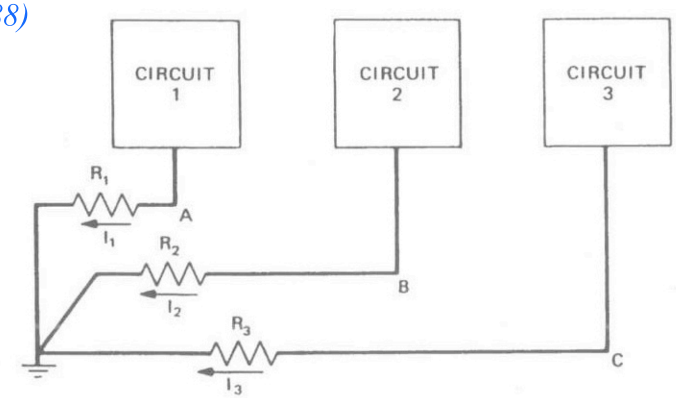


Figure 3-7. *Separate ground system is a parallel ground connection and provides good low-frequency grounding but is mechanically cumbersome.*

- f > 1 MHz
- minimize R and especially L to minimize potentials w.r.t. local ground plane, discourage radiation & wave reception

- f < 100 kHz
- minimize R to minimize absolute voltage drop, but more important..
- minimize interactions between circuits; A, B and C drop out of performance of ckts 1,2,3.

Hybrid Grounding

from Ott (1988)

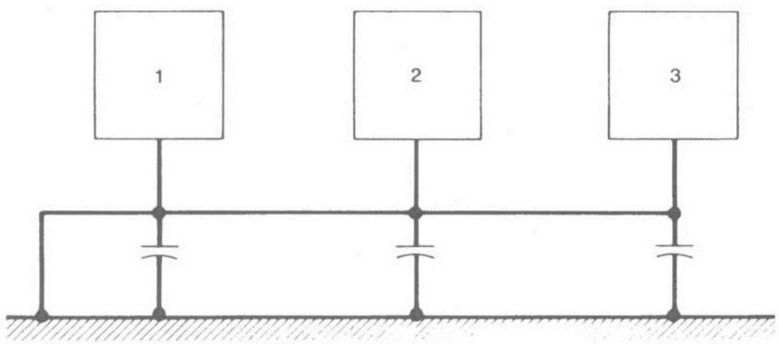
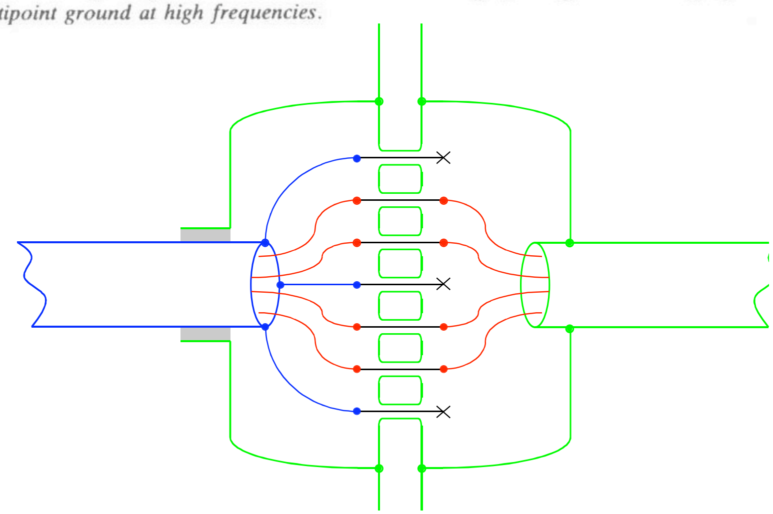


Figure 3-9. *A hybrid ground connection that acts as a single-point ground at low frequencies and a multipoint ground at high frequencies.*



- Capacitive shunts enforce RF ground plane
- 60 Hz and other LF current still forced to single-point ground
- Free parameter: *crossover frequency*

possible implementation (see jay's talk)

Analog Circuit Protection

- Lesson 4: Shield all boards, crates, cross-connects *(even if self-made EMI is "eliminated")*
  - Analog circuits susceptible to electrostatic, magnetic coupling as well as RF reception; μV - nV levels unattainable even in quietest environments without Faraday shielding
  - Backplane I/O (controls, monitoring, power) a significant source of conducted coupling
- Recommendations (still under development):
  - Replace Eurocard crates with shielded versions (similar to VME crates)
  - Introduce EMI filters on analog conductor penetrations also
  - Retrofit "shield kits" (e.g., VXI form) to enclose existing analog boards
  - Introduce backplane extenders with EMI filtering, optoisolation, etc.
  - Replace open cross-connect functions with compact enclosed/shielded system (several concepts on the drawing board)

Overriding lesson: TEST IT

- Lesson 5: Test for EMC & find trouble before it bites
  - Before installation (bench, test range or chamber)
    - Diagnostics & corrective measures impeded or precluded once it's in the machine
    - Begin at design/prototyping stage
    - Look for both emission *and* susceptibility (can be difficult)
  - After installation (experiment floor)
    - Snoop for collective interactions, new "external" sources, unauthorized (or unwise) configuration changes
    - Keep an environmnental baseline for diagnosing future exceptions
- Response: Build up capability, add EMC to acceptance criteria
  - Propose to start with limited investments in outdoor test ranges and analysis equipment at observatory sites
  - Will reevaluate after some program experience & (more) outside consultation